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Khoshgard et al.

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(54) **CHANNEL ESTIMATION IN OFDM TRANSMISSION SYSTEM AND METHOD**

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(51) **Int. Cl.**
H04L 27/26 (2006.01)
H04L 5/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H04L 27/2647*** (2013.01); ***H04L 5/005*** (2013.01); ***H04L 5/0007*** (2013.01); ***H04L 25/0232*** (2013.01); ***H04L 25/03821*** (2013.01); *H04L 5/0023* (2013.01); *H04L 5/0048* (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC ... H04L 5/0007; H04L 5/0048; H04L 5/0023; H04L 5/005; H04L 5/0051
USPC 375/260, 267, 295, 316, 340; 370/203, 370/208, 210, 252, 328–330
See application file for complete search history.

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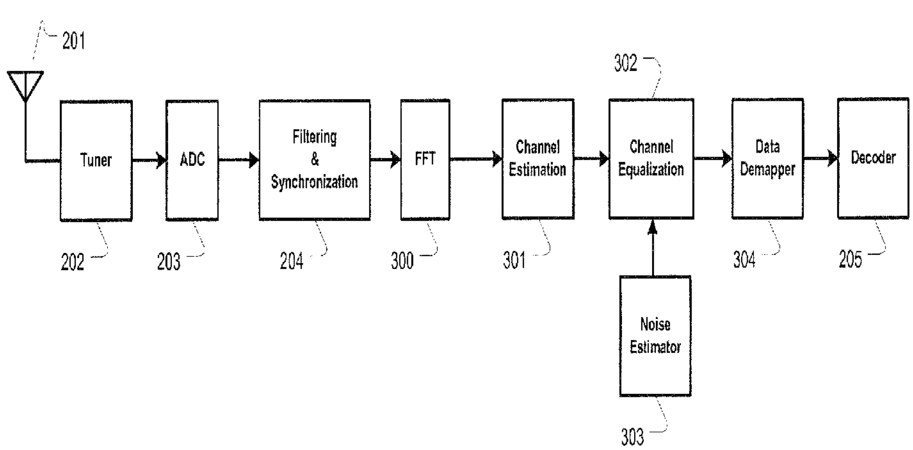
(57) **ABSTRACT**

A system and method is provided for estimating the channel in OFDM transmission with inter-carrier interference (ICI). A channel in a data subcarrier in a subchannel shared between pilot subcarriers and data subcarriers can be estimated by performing interpolation based on estimated channels in pilot subcarriers in the same OFDM symbol as the subcarrier, such as through spline interpolation. A second estimate of the channel in the subcarrier can be produced by averaging an estimate of the channel in a subcarrier in the subchannel in a previous OFDM symbol and an estimate of the channel in a subcarrier in the subchannel in a succeeding OFDM symbol. A third estimate of the channel in the subcarrier can be produced through a linear combination of the first estimate and the second estimate. The channel in data subcarriers can be estimated through a weighted sum of the channel in nearest subcarriers.

17 Claims, 18 Drawing Sheets



(51) **Int. Cl.**
H04L 25/02 (2006.01)
H04L 25/03 (2006.01)

(52) **U.S. Cl.**
CPC *H04L 5/0051* (2013.01); *H04L 2025/03414* (2013.01)

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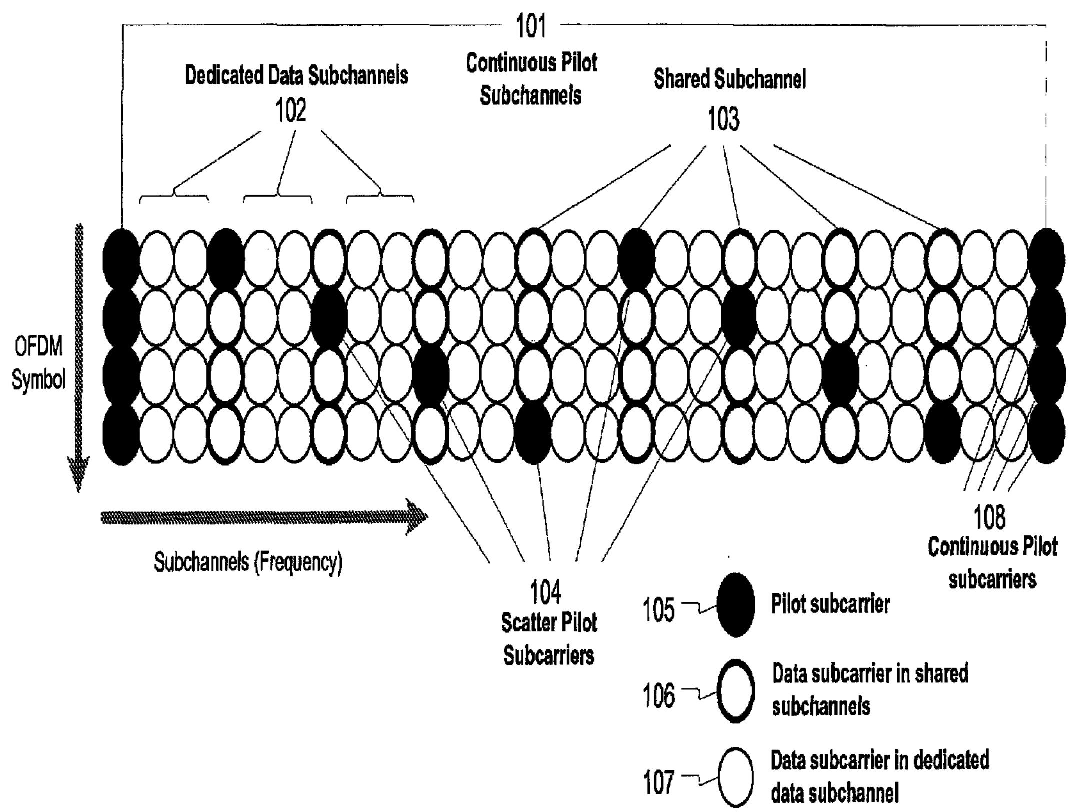
101
Dedicated Data Subchannels
102
Continuous Pilot Subchannels
Shared Subchannel
103
OFDM Symbol
Subchannels (Frequency)
104
Scatter Pilot Subcarriers
108
Continuous Pilot subcarriers
105
Pilot subcarrier
106
Data subcarrier in shared subchannels
107
Data subcarrier in dedicated data subchannel

Figure 1

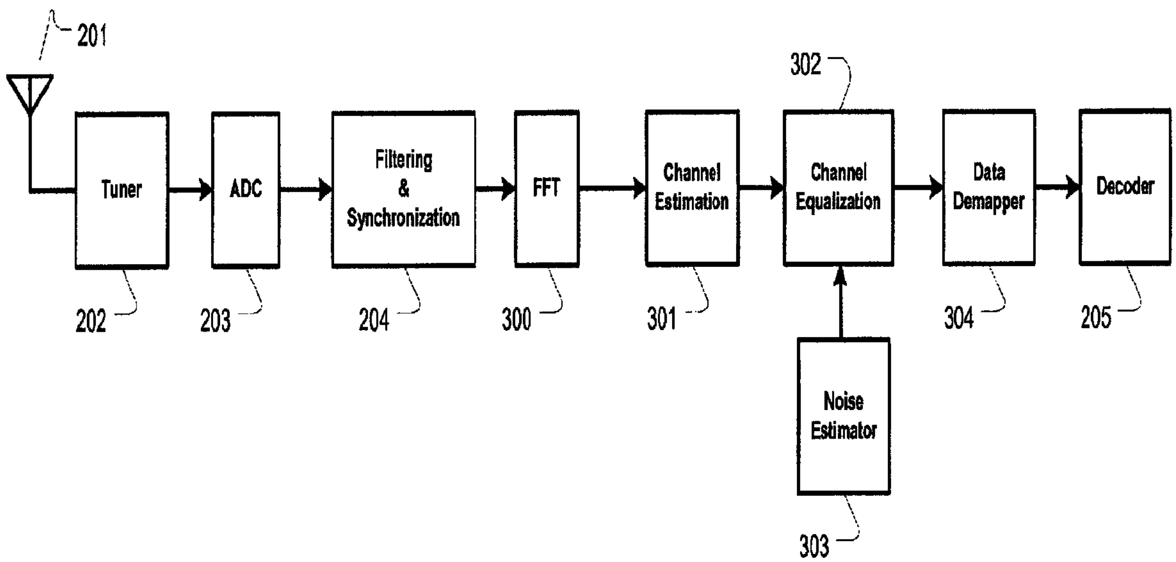
201
Tuner
ADC
Filtering
&
Synchronization
FFT
Channel
Estimation
302
Channel
Equalization
Data
Demapper
Decoder
202
203
204
300
301
304
205
Noise
Estimator
303

Figure 2

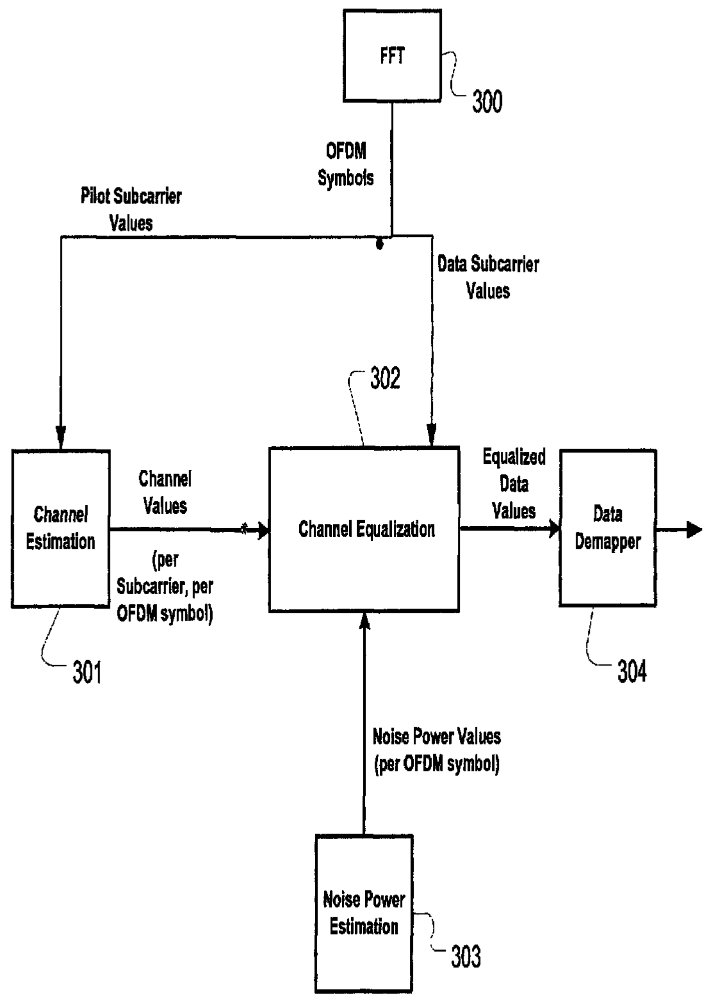
FFT
300
OFDM Symbols
Pilot Subcarrier Values
Data Subcarrier Values
302
Channel Estimation
Channel Values
(per Subcarrier, per OFDM symbol)
Channel Equalization
Equalized Data Values
Data Demapper
301
304
Noise Power Values (per OFDM symbol)
Noise Power Estimation
303

Figure 3

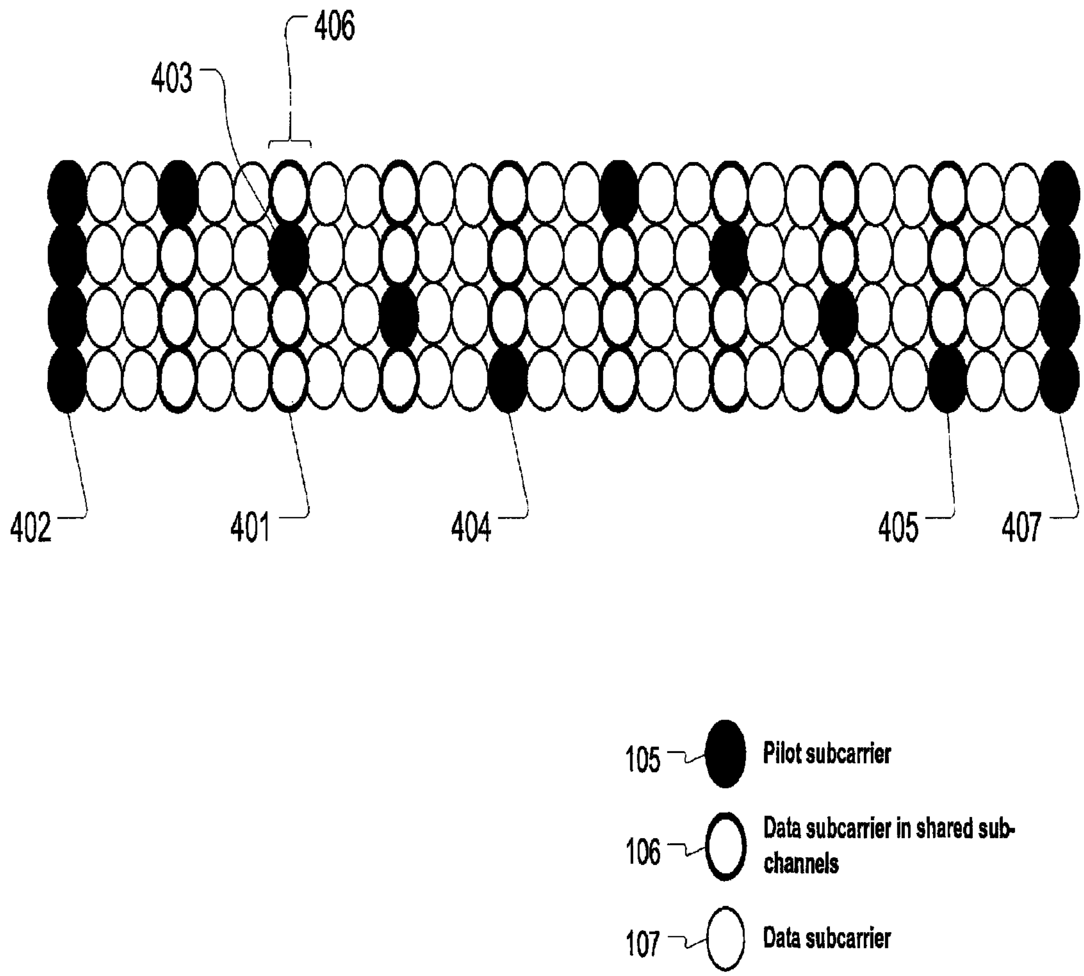
406
403
402
401
404
405
407
105
Pilot subcarrier
106
Data subcarrier in shared sub-channels
107
Data subcarrier

Figure 4

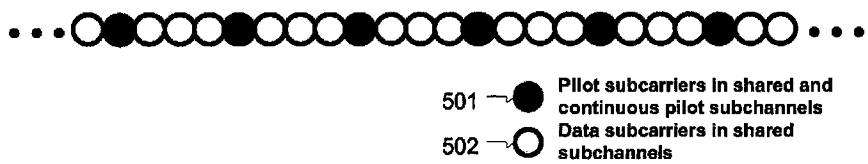

Figure 5

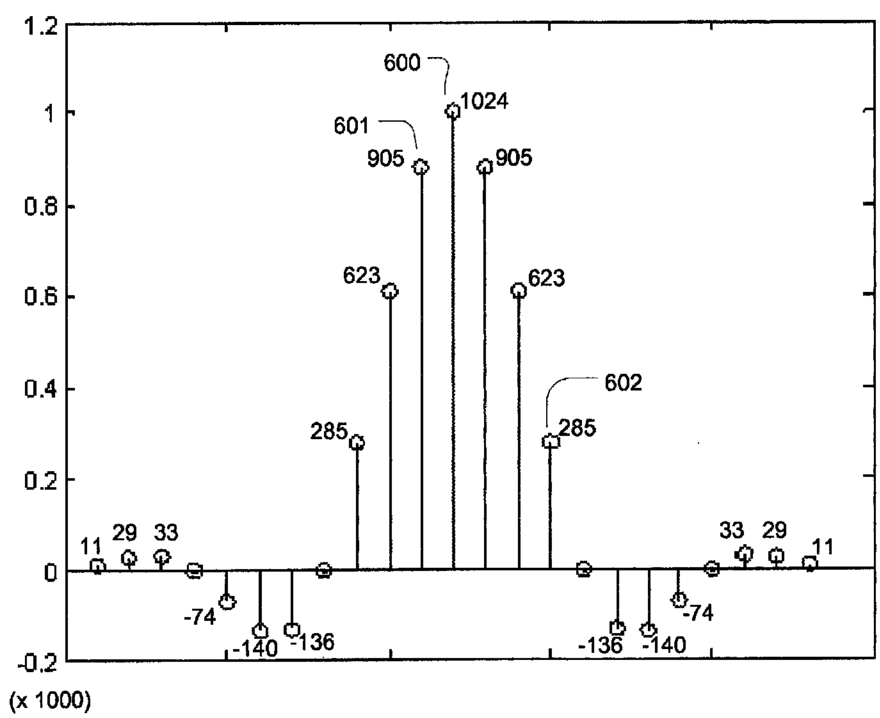

Figure 6

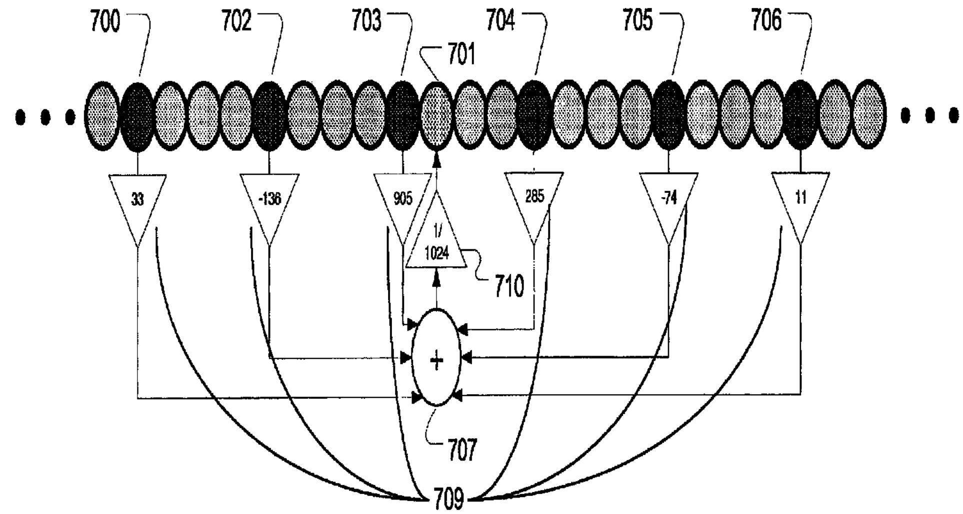

Figure 7

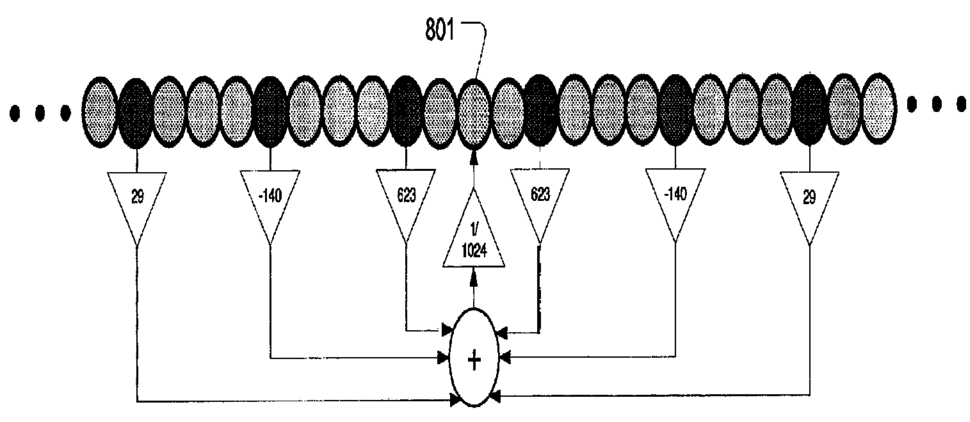

Figure 8

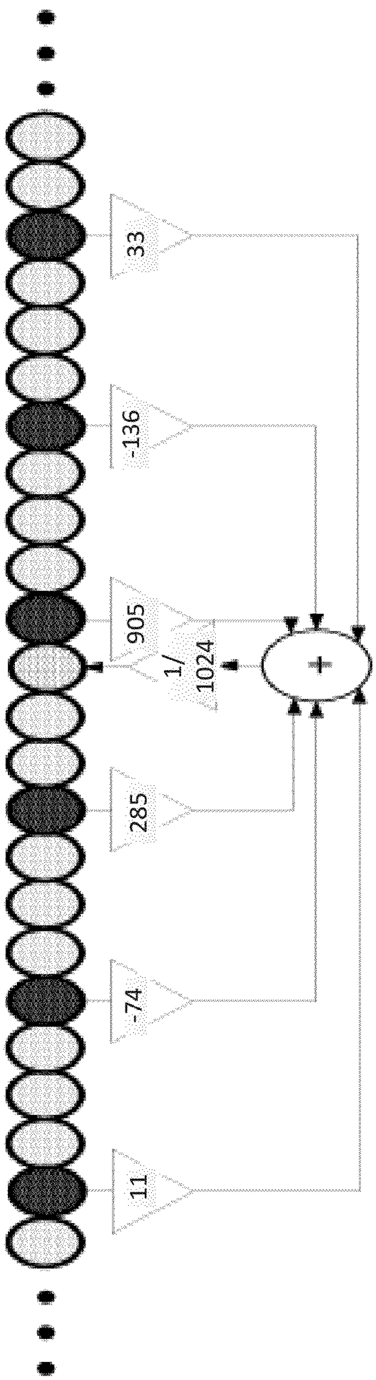
33
-136
905
1/
1024
+
285
-74
11

FIG. 9

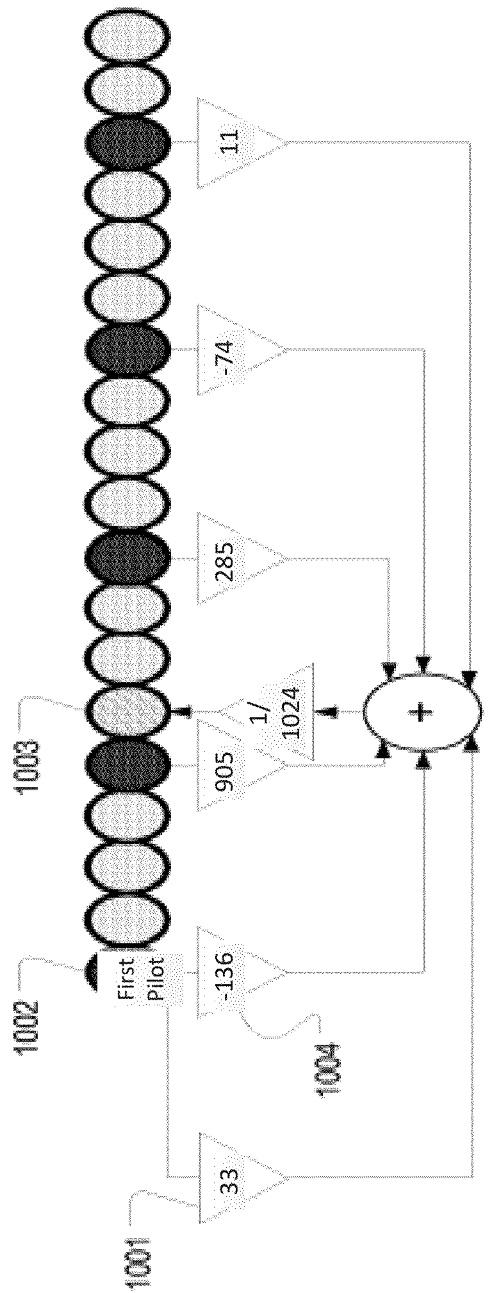
11
-74
285
1/
1024
+
905
1003
First
Pilot
1002
-136
1004
33
1001

FIG. 10

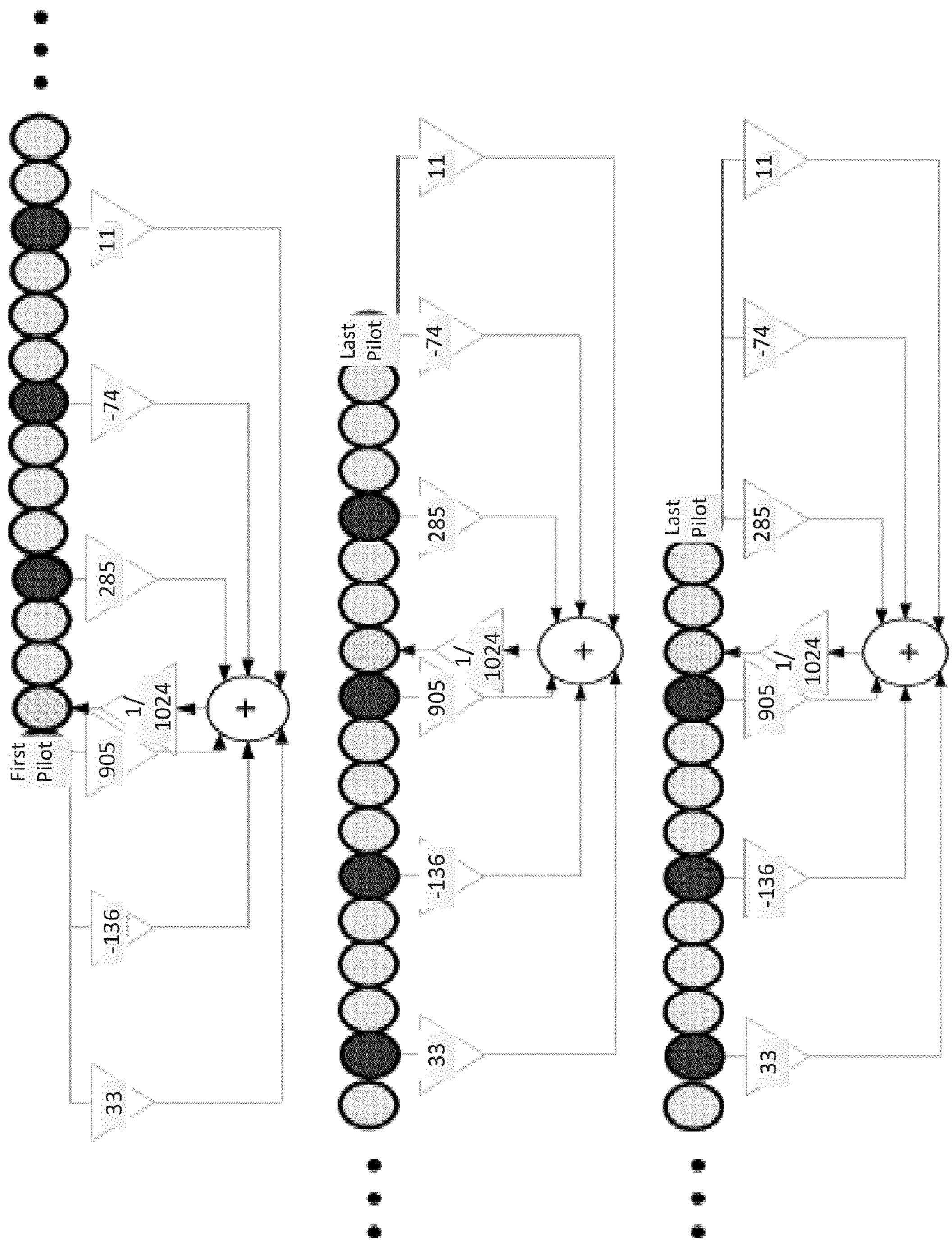

FIG. 11

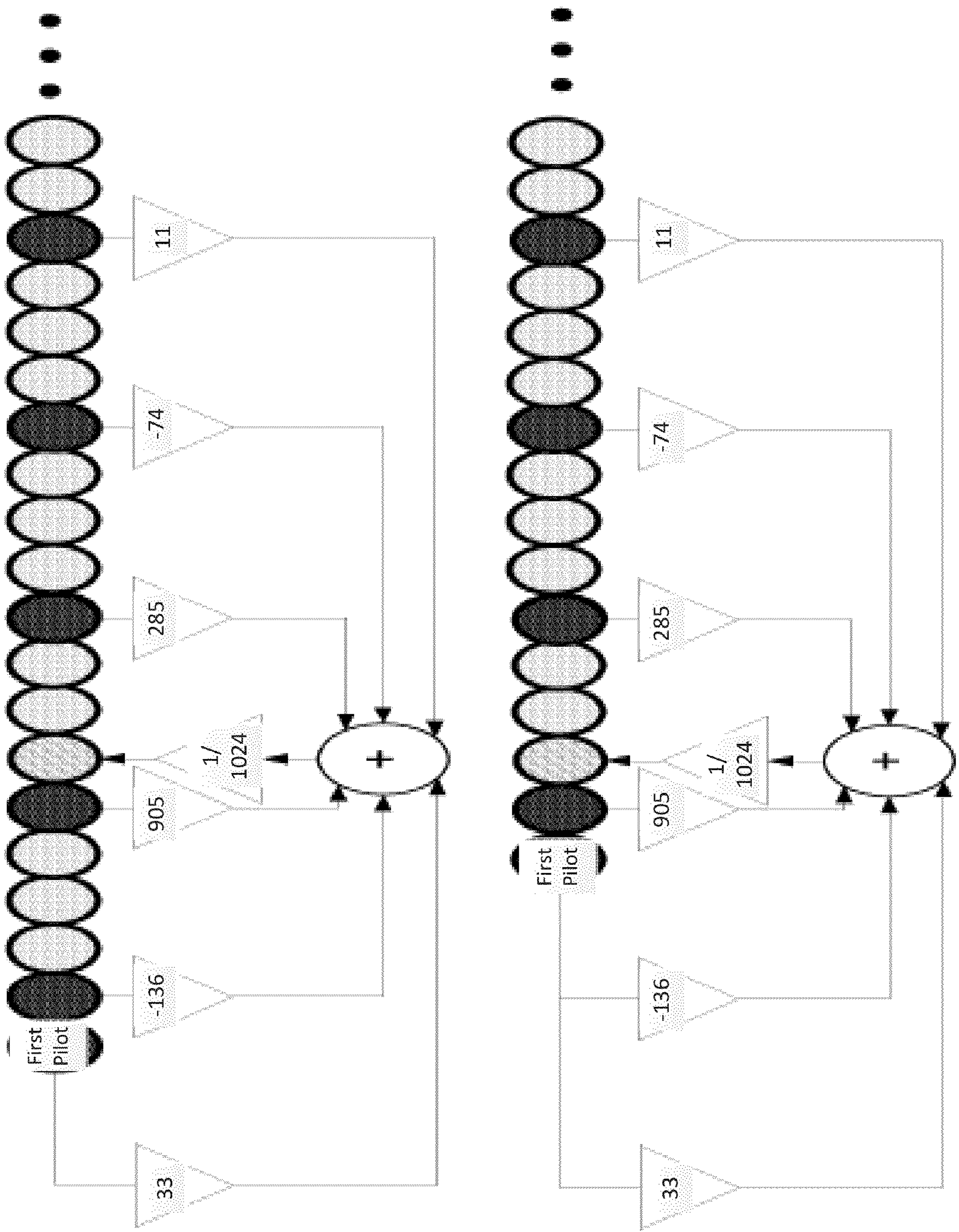
11
-74
285
1/1024
905
-136
33
First Pilot
+
11
-74
285
1/1024
905
-136
33
First Pilot
+

FIG. 12

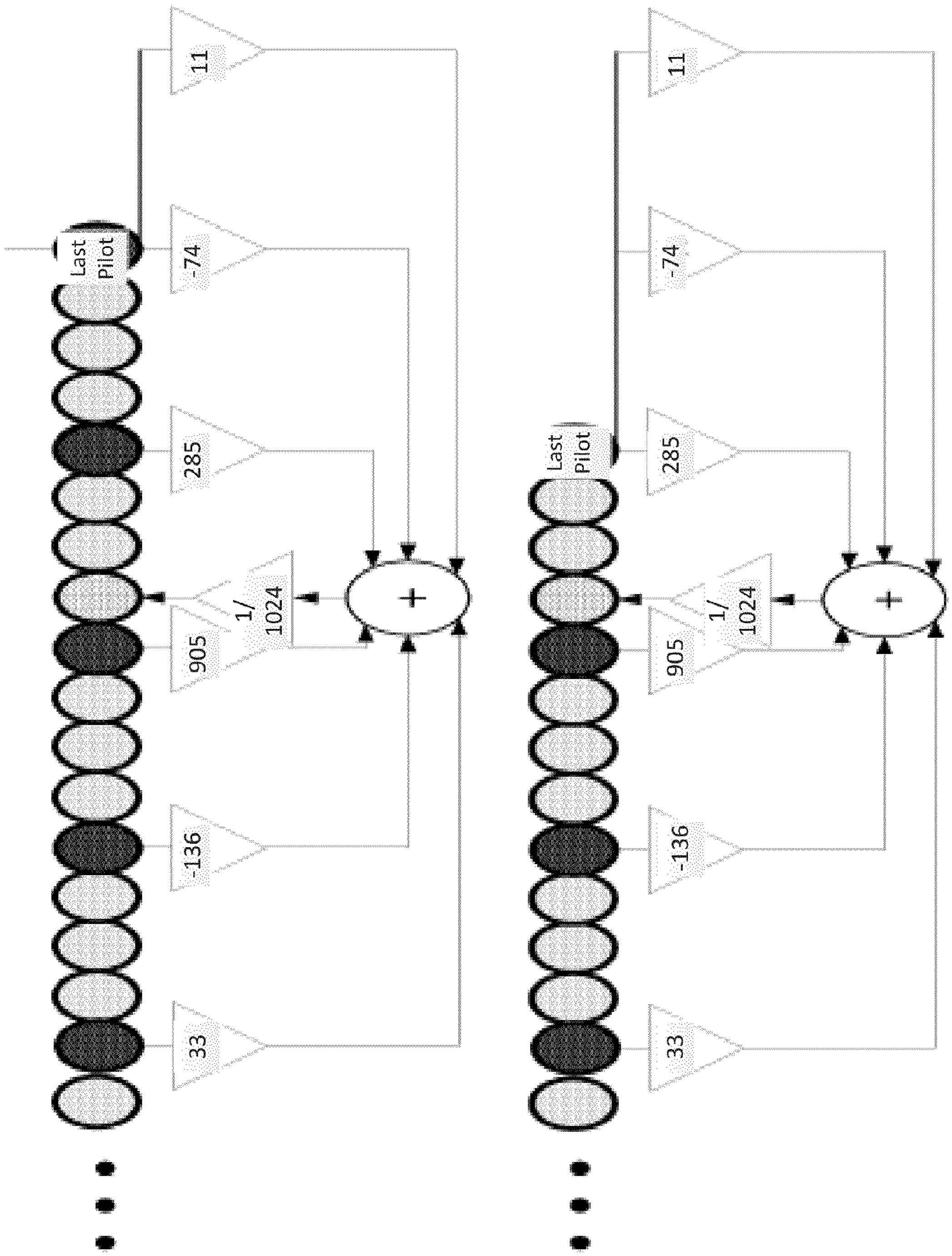
Last Pilot
11
-74
285
1/ 1024
905
+
-136
33
Last Pilot
11
-74
285
1/ 1024
905
+
-136
33

FIG. 13

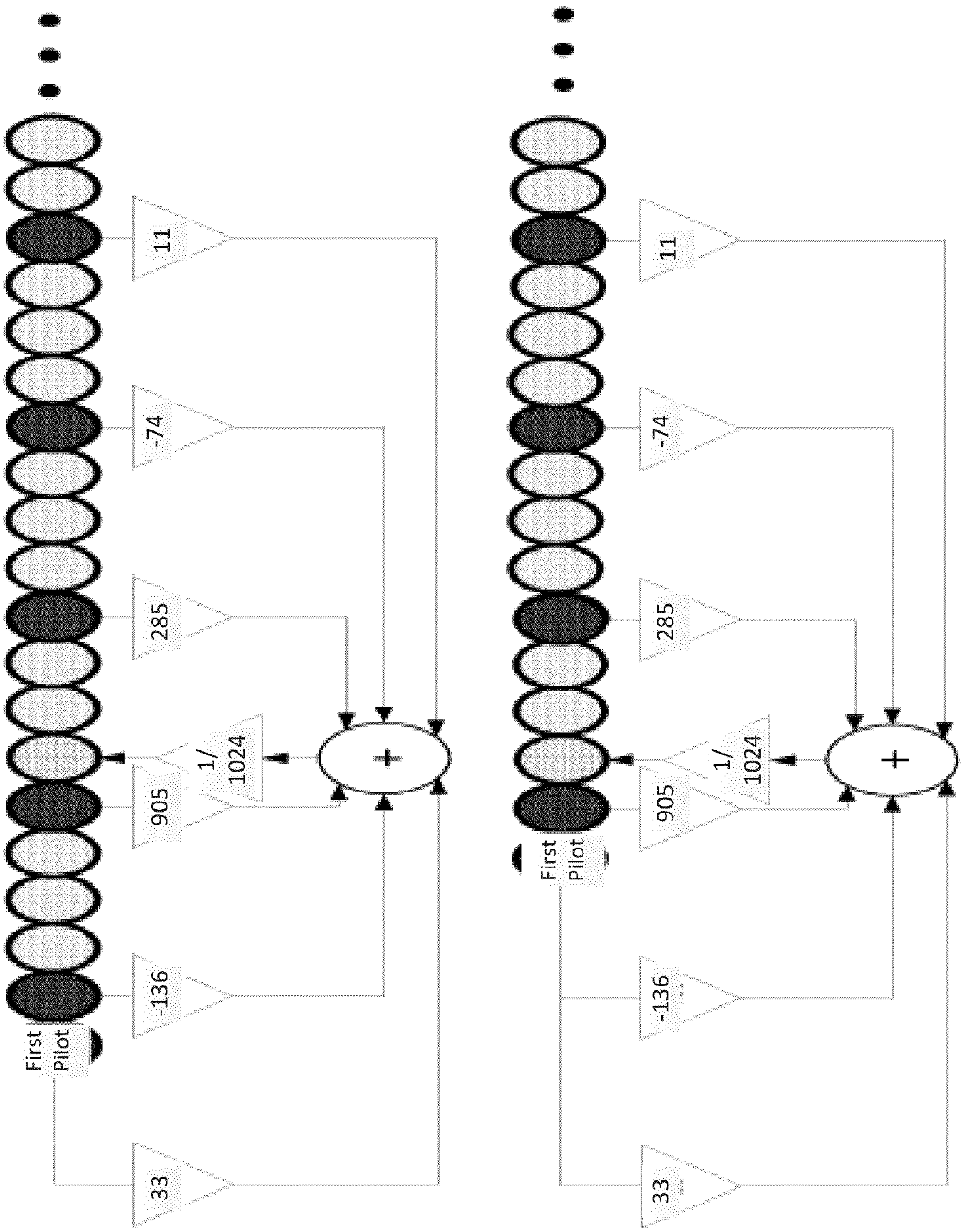
11
-74
285
1/
1024
905
-136
33
First
Pilot
+
11
-74
285
1/
1024
905
First
Pilot
-136
33
+

FIG. 14

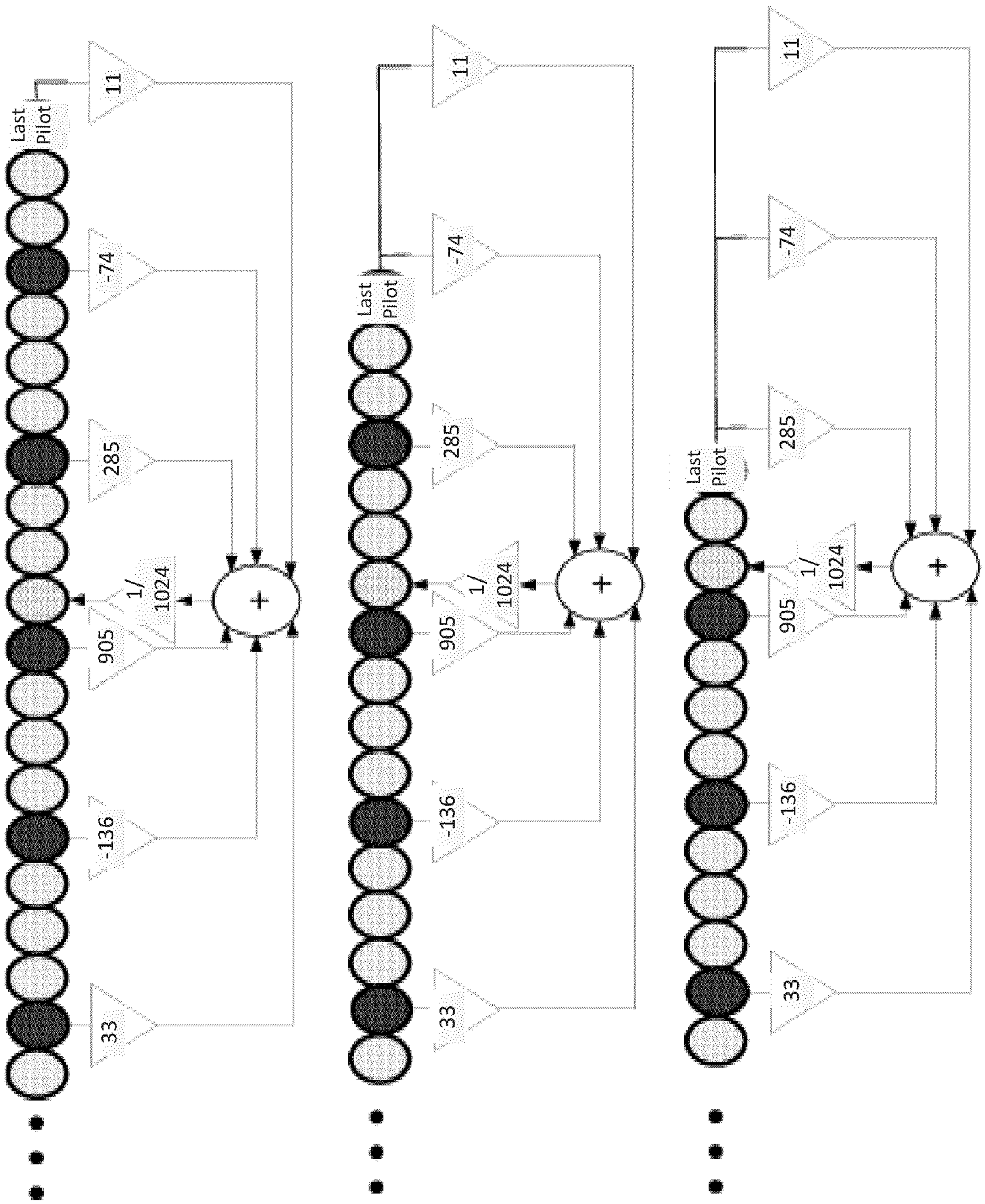

FIG. 15

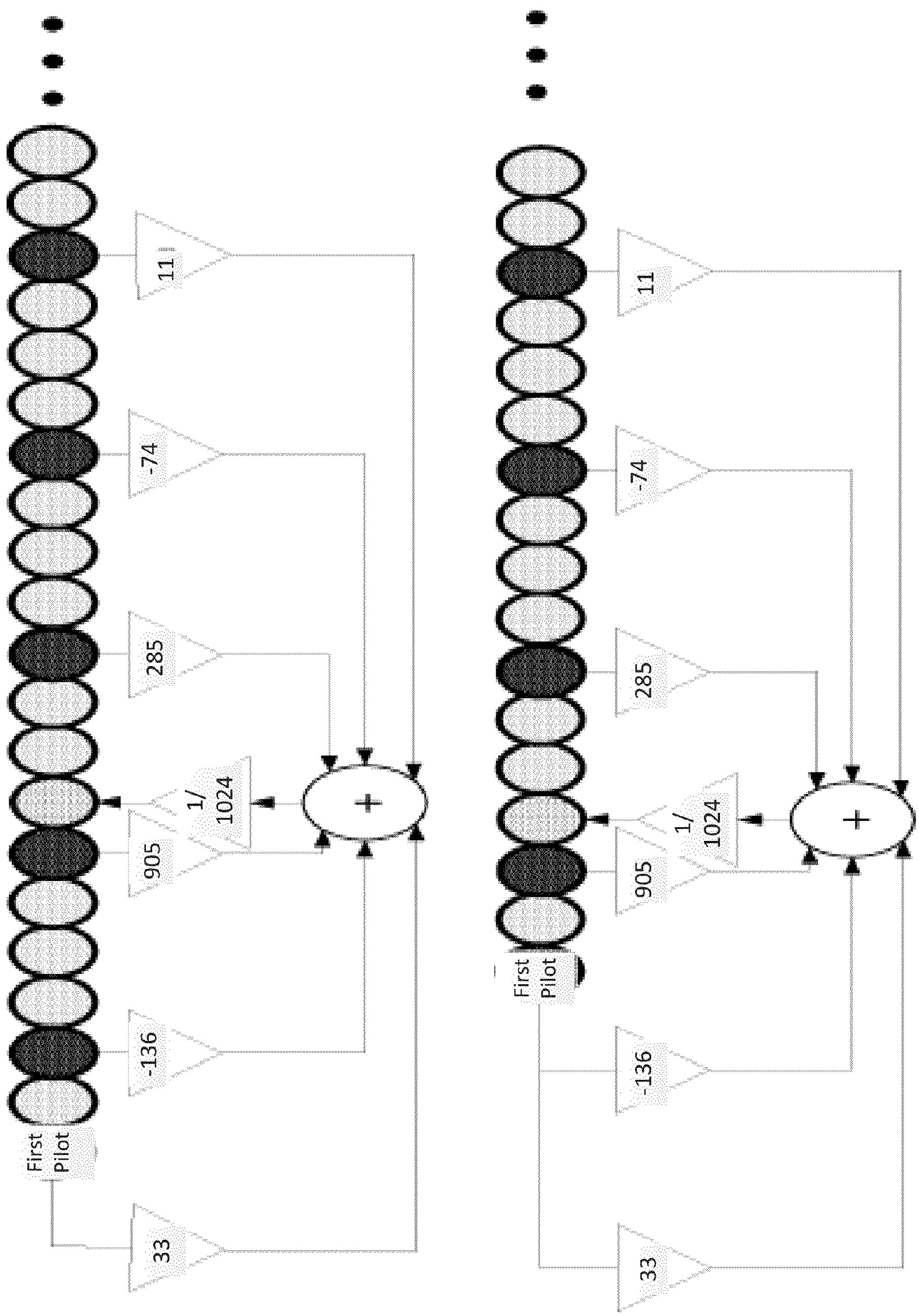
11
-74
285
1/
1024
+
905
-136
First
Pilot
33
11
-74
285
1/
1024
+
905
First
Pilot
-136
33

FIG. 16

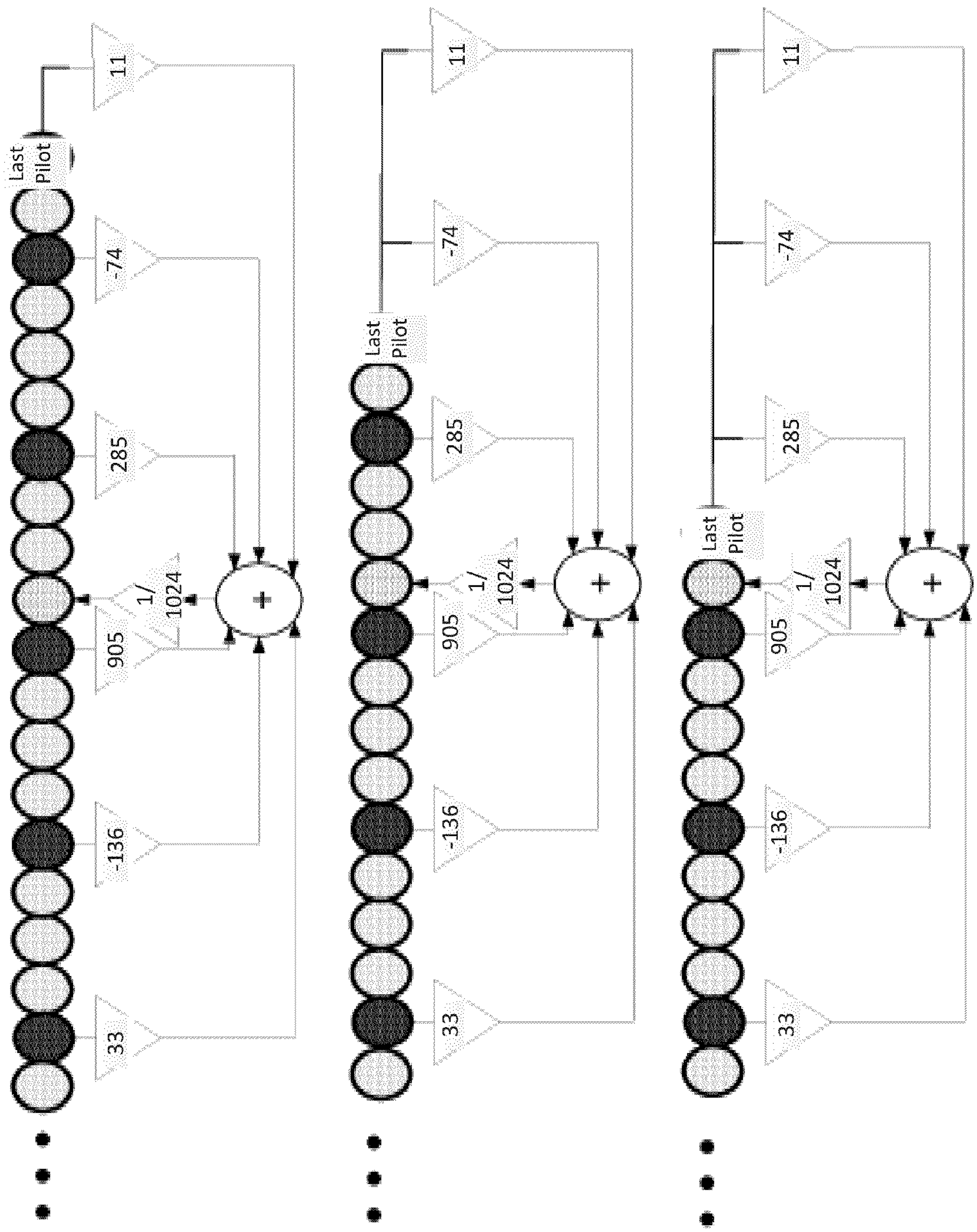

FIG. 17

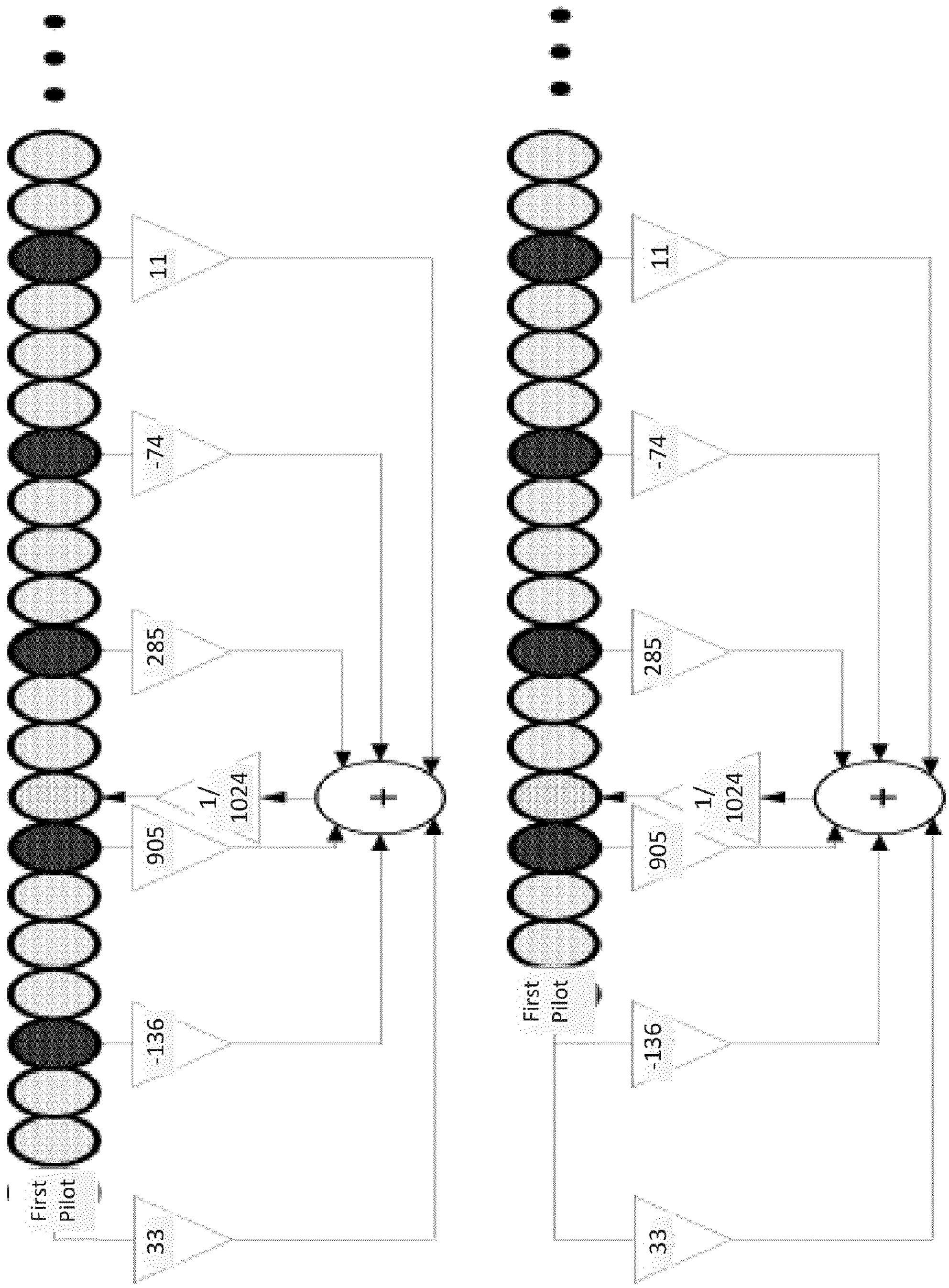
11
-74
285
1/
1024
905
-136
33
+
First
Pilot
11
-74
285
1/
1024
905
-136
33
+
First
Pilot

FIG. 18

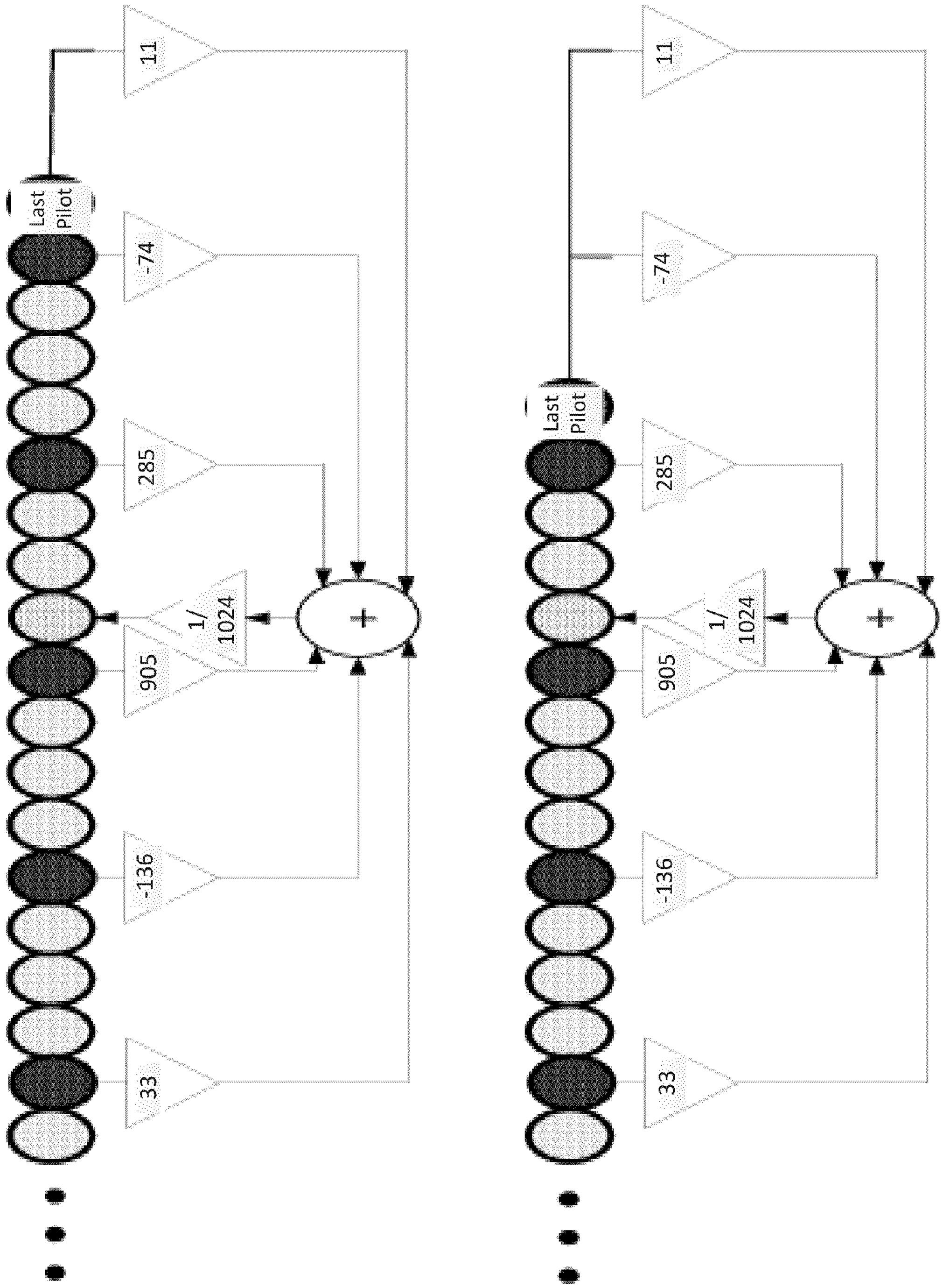
11
Last Pilot
-74
285
1/1024
+
905
-136
33
11
-74
Last Pilot
285
1/1024
+
905
-136
33

FIG. 19

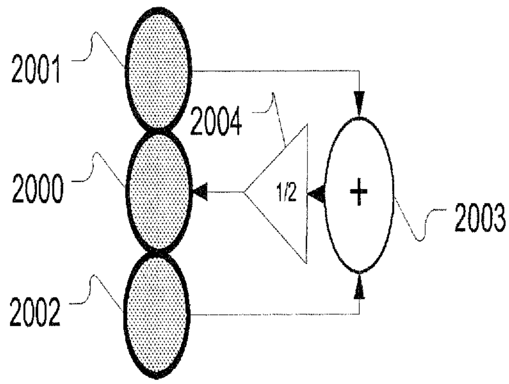

Figure 20A

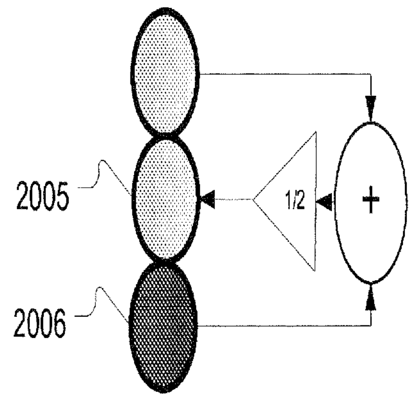

Figure 20B

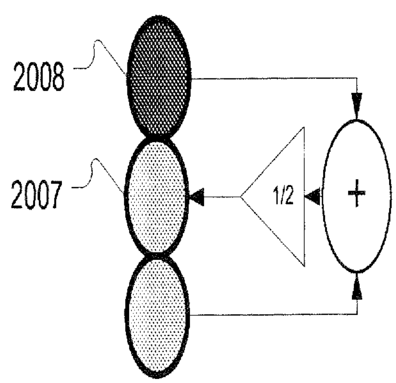

Figure 20C

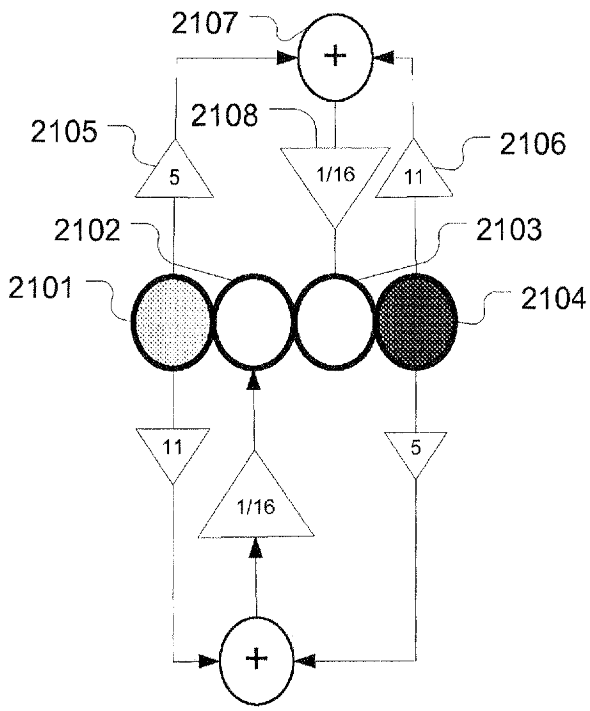

Figure 21A

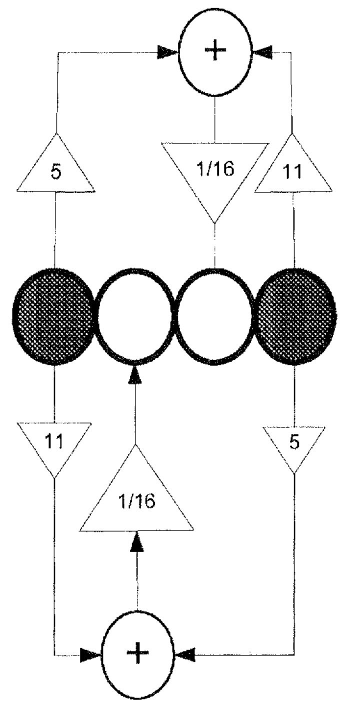

Figure 21B

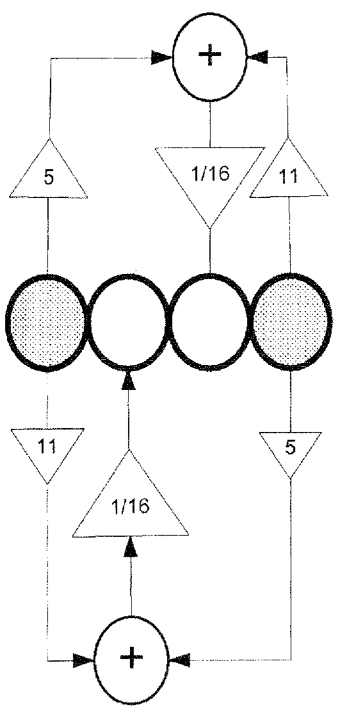

Figure 21C

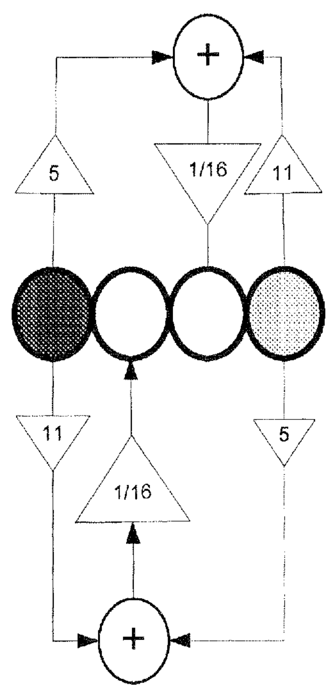

Figure 21D

CHANNEL ESTIMATION IN OFDM TRANSMISSION SYSTEM AND METHOD

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a continuation of allowed U.S. patent application Ser. No. 12/790,743 entitled "CHANNEL ESTIMATION IN OFDM TRANSMISSION SYSTEM AND METHOD," filed May 28, 2010, of which the full disclosure of this application is incorporated herein by reference for all purposes.

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FIELD OF THE INVENTION

This invention relates generally to the field of wireless communication, and more specifically to channel estimation in Orthogonal Frequency-Division Multiplexing (OFDM) transmission.

BACKGROUND

In the age of information, the field of communications devices has experienced among the most rapid rates of innovation of any area of technology. As the requirements of communication devices continue to increase, methods for faster, cheaper, and more reliable data transfer are continuously developed. Orthogonal frequency-division multiplexing (OFDM) has developed as a method for reliable, high-volume data transfer in both wire and wireless mediums that can require simpler device architecture than other methods. Wideband digital applications such as digital television, audio broadcasting, wireless networking, and broadband internet have become popular applications for OFDM transmission.

Generally, in OFDM transmission, when the transmission channel is fixed in time and there is no Doppler effect, cross-talk between subchannels can be eliminated by selecting subcarrier frequencies so that subcarriers are orthogonal to each other. Hence, data sent through such OFDM transmission can be recovered from a received signal by estimating the channel in each subcarrier and compensating the signal for the estimated channel without taking into account inter-carrier interference (ICI).

However, in certain cases, such as when the Doppler Effect is present, subcarrier frequencies can become distorted. As a result, the subcarriers may no longer be orthogonal, resulting in cross-talk between subchannels and inter-carrier interference. In these situations, methods for data recovery that do not take into account inter-carrier interference can be insufficient to retrieve the transmitted data. What is needed is a system and method that estimates the channel taking into account inter-carrier interference so that channel equalization can compensate for inter-carrier interference based on the estimated channel.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an example of an OFDM signal with scatter pilots, which can be similar to signals in the DVB-T/H and ISDB-T standards.

FIG. **2** illustrates an example of an OFDM receiver with a Channel Estimation and a Channel Equalization module, in accordance with various embodiments.

FIG. **3** illustrates an example a Channel Estimation and a Channel Equalization module, in accordance with various embodiments.

FIG. **4** illustrates an example of channel estimation in an OFDM transmission.

FIG. **5** illustrates an example of an OFDM symbol with dedicated data subcarriers omitted for the sake of illustration;

FIG. **6** illustrates a graphical example of the impulse response of a filter that can be implemented to perform interpolation, in accordance with various embodiments.

FIG. **7** illustrates an example calculation of a channel in a subcarrier in a shared subchannel to the right of a pilot subcarrier by spline interpolation that can be implemented in a filter, in accordance with various embodiments.

FIG. **8** illustrates an example calculation of a channel in a subcarrier in a shared subchannel between two successive shared subchannels by spline interpolation that can be implemented in a filter, in accordance with various embodiments.

FIG. **9** illustrates an example calculation of a channel in a subcarrier in a shared subchannel to the left of a pilot subcarrier by spline interpolation that can be implemented in a filter, in accordance with various embodiments.

FIG. **10** illustrates an example calculation of the channel in a subcarrier when a pilot subcarrier is missing, in accordance with various embodiments.

FIG. **11** illustrates further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

FIG. **12** illustrates further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

FIG. **13** illustrates further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

FIG. **14** illustrates further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

FIG. **15** illustrates further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

FIG. **16** illustrates further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

FIG. **17** illustrates further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

FIG. **18** illustrates further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

FIG. **19** illustrates further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

FIG. **20**A illustrates an example estimation of a channel in a data subcarrier in a shared subchannel based on an estimate of the channel in a subcarrier in the subchannel of the previous OFDM symbol and an estimate of the channel in the subcarrier in the subchannel of the next OFDM symbol, in accordance with various embodiments.

FIG. **20**B illustrates an example estimation of a channel in a data subcarrier in a shared subchannel based on an estimate of the channel in a subcarrier in the subchannel of the previous OFDM symbol and an estimate of the channel in the subcarrier in the subchannel of the next OFDM symbol, when the subcarrier in the subchannel of the next OFDM symbol is a pilot subcarrier, in accordance with various embodiments.

FIG. **20**C illustrates an example estimation of a channel in a data subcarrier in a shared subchannel based on an estimate of a channel in a subcarrier in the subchannel of the previous OFDM symbol and an estimate of the channel in the subcarrier in the subchannel of the next OFDM symbol, when the subcarrier in the subchannel of the previous OFDM symbol is a pilot subcarrier, in accordance with various embodiments.

FIG. **21**A illustrates an example of channel estimation in a data subcarrier in adedicated data subchannel through the weighted sum of the channel in two nearest estimated subcarriers, in accordance with various embodiments.

FIG. **21**B illustrates an example of channel estimation in a data subcarrier in adedicated data subchannel through the weighted sum of the channel in two nearest estimated pilot subcarriers, in accordance with various embodiments.

FIG. **21**C illustrates an example of channel estimation in a data subcarrier in a dedicated data subchannel through the weighted sum of the channel in two nearest estimated data subcarriers, in accordance with various embodiments.

FIG. **21**D illustrates an example of channel estimation in a data subcarrier in a dedicated data subchannel through the weighted sum of the channel in a nearest estimated data subcarrier and a nearest estimated pilot subcarrier, in accordance with various embodiments.

DETAILED DESCRIPTION OF THE DRAWINGS

In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. However, it will be apparent to one skilled in the art that the present invention can be practiced without these specific details. In other instances, well known circuits, components, algorithms, and processes have not been shown in detail or have been illustrated in schematic or block diagram form in order not to obscure the present invention in unnecessary detail. Additionally, for the most part, details concerning communication systems, transmitters, receivers, communication devices, computers, and the like have been omitted inasmuch as such details are not considered necessary to obtain a complete understanding of the present invention and are considered to be within the understanding of persons of ordinary skill in the relevant art. It is further noted that, where feasible, all functions described herein may be performed in either hardware, software, firmware, analog components or a combination thereof, unless indicated otherwise. Certain term are used throughout the following description and claims to refer to particular system components. As one skilled in the art will appreciate, components may be referred to by different names. This document does not intend to distinguish between components that differ in name, but not function. In the following discussion and in the Claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus should be interpreted to mean "including, but not limited to . . . ".

Embodiments of the present invention are described herein. Those of ordinary skill in the art will realize that the following detailed description of the present invention is illustrative only and is not intended to be in any way limiting. Other embodiments of the present invention will readily suggest themselves to such skilled persons having the benefit of this disclosure. Reference will be made in detail to implementations of the present invention as illustrated in the accompanying drawings. The same reference indicators will be used throughout the drawings and the following detailed description to refer to the same or like parts.

In the interest of clarity, not all of the routine features of the implementations described herein are shown and described. It will, of course, be appreciated that in the development of any such actual implementation, numerous implementation-specific decisions must be made in order to achieve the developer's specific goals, such as compliance with applications and business-related constraints, and that these specific goals will vary from one implementation to another and from one developer to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking of engineering for those of ordinary skill in the art having the benefit of this disclosure.

In various embodiments, systems and methods are described for estimating a channel in OFDM transmission containing scatter pilot signals. Generally, OFDM signals can be sent over a wire medium, such as cabling, or wireless medium, such as air. When the signal travels through a medium, it may become affected by the medium. The effect can be referred to as the "channel." By estimating the channel and applying an inverse function of the channel to a received signal, an original transmitted signal can be recovered from an affected received signal; in other words, the transmitted data can be equalized.

FIG. **1** illustrates an example of an OFDM signal with scatter pilots, which can be similar to signals in the DVB-T/H and ISDB-T standards. Each horizontal row of circles represents an OFDM symbol. Each vertical row of circles represents a subchannel. Each circle in the figure is a subcarrier, which is a subchannel of an OFDM symbol. The frequency of the subchannels can increase from left to right. Subchannels that contain only pilot subcarriers **105** are continuous pilot subchannels **101** and pilot subcarriers in continuous pilot subchannels **101** are continuous pilot subcarriers **108**. Subchannels that contain pilot subcarriers **105** and data subcarriers **106** are shared subchannels **103**. Data subcarriers in shared subchannels **106** are represented by white circles with a bold outline in FIG. **1**. Scatter pilot subcarriers **104** are pilot subcarriers **105** in shared subchannels **103**. Dedicated data subchannels **102** contain only data subcarriers **107**, represented by white circles with non-bold outline in the figure.

FIG. **1** illustrates a general example of an OFDM signal. Various types of OFDM signals in various standards may contain different numbers and configurations of pilot subcarriers, data subcarriers, dedicated data subchannels, shared subchannels, continuous pilot subchannels and other components than illustrated in FIG. **1**. As one skilled in the art would appreciate, this disclosure is not limited to any particular configuration or type of OFDM signal.

In various embodiments, Channel Estimation can be performed to measure the channel in an OFDM transmission. The channel in an OFDM transmission can be estimated by estimating the channel in the subcarriers. Namely, each transmitted subcarrier can be affected by the environment and the medium through which the signal travels when the signal is transmitted. The channel in each subcarrier is effect that such transmission has had on the data in the subcarrier. In various embodiments, the channels in subcarriers in an OFDM signal can be estimated based on pilot subcarriers. The channel in pilot subcarriers can be estimated at the receiver based on a measured subcarrier value and an expected, known subcarrier value. The channel in the remaining, non-pilot subcarriers can be estimated based on the estimated channel in pilot subcarriers. Thus, the channel can be estimated in every subcarrier of every OFDM symbol. Once the channel is estimated, Channel Equalization can be performed to compensate the data signals for the channel to recover original transmitted data.

FIG. **2** illustrates an example of an OFDM receiver with a Channel Estimation and a Channel Equalization module, in accordance with various embodiments. A signal can be received through an antenna **201**. The signal can be conveyed to a tuner **202**, where the signal can be amplified, filtered, and/or down-converted, for example to a baseband or intermediate frequency (IF). After the tuner **202**, the signal can be conveyed to an Analog to Digital Converter (ADC) **203** for analog to digital conversion. The signal can then be conveyed to a filtering and synchronization module **204** for further filtering and synchronization and then to a Fast Fourier Transform (FFT) module **300**. The FFT module **300** can output OFDM symbols. The OFDM symbols can be conveyed to a Channel Estimation module **301**, where the channel can be estimated based on the pilot signals. OFDM symbols, the estimated channel, as well as noise power data from a Noise Estimator module **303** can be conveyed to the Channel Equalization module **302**, where equalized data values can be produced. The equalized data values can then be conveyed to a Data Demapper **304** and to a Decoder **205** for further processing.

FIG. **3** illustrates an example of a Channel Estimation and a Channel Equalization module, in accordance with various embodiments. OFDM symbols can be conveyed from the FFT module **300**. Pilot subcarrier values can be conveyed to the Channel Estimation module **301** and data subcarrier values can be conveyed to the Channel Equalization module **302**. In the Channel Estimation module **301**, the channel in subcarriers can be estimated based on the pilot subcarrier values, as will be described in greater detail below. In various embodiments, a channel in every subcarrier, in every OFDM symbol can be estimated. The estimated channel values from the channel estimation module **301**, data subcarrier values from the FFT module **300**, and noise power data per OFDM symbol from a noise power estimation module **303** can be conveyed to the Channel Equalization module **302**. In the Channel Equalization module **302**, data subcarrier values can be adjusted, or "equalized", based on the estimated channel in each subcarrier value and the noise power data. The equalized data values can be conveyed to a Data Demapper **304** for further processing.

Generally, the channel in a pilot subcarrier can be estimated directly based on the expected value of the pilot subcarrier and the measured value of the pilot subcarrier. For example, the channel in a pilot subcarrier can be estimated by dividing the measured value of the subcarrier by the expected value of the subcarrier. The channel in data subcarriers in dedicated data subchannels and shared subchannels cannot be estimated directly, as it can be in pilot subcarriers, because the expected value in those subcarriers is not known at the receiver. However, in data subcarriers, the channel can be estimated based on the estimated channel in nearby pilot subcarriers.

FIG. **4** illustrates an example of channel estimation in an OFDM transmission, in accordance with various embodiments. In a transmission with a time-invariant channel; that is, where the channel substantially does not change over time, the channel in each subcarrier of a subchannel will be constant. However, the channel may differ across different channels. For instance, in the illustrated example, if the channel in the transmission is time invariant, then the channel in the subchannel **406** will be constant, in other words, the channel in each subcarrier of the subchannel **406** will be substantially the same. Hence, the channel in each of the four illustrated subcarriers of the subchannel will be approximately the same. In such a scenario, the channel in the pilot subcarrier **403** can be an accurate estimate of the channel in the data subcarrier **401**. Hence, in a time invariant channel, an estimate of a channel in a pilot subcarrier can be used to estimate the channel in another data subcarrier in the same subchannel.

However, if the channel in a transmission is time-variant, then the channel in a subchannel can change from one OFDM symbol to the next. For example, this can be the case when the Doppler Effect is present. In such cases, the estimated channel in a pilot subcarrier in a subchannel, such as the pilot subcarrier **403** in FIG. **4**, may provide a poor estimate of the channel in another data subcarrier in the subchannel, such as the data subcarrier **401**. However, because adjacent parts of each symbol can be received near in time to each other, time-variant effects can be substantially consistent throughout a symbol or portions of a symbol. In this case, estimated channels in pilot subcarriers in an OFDM symbol can be used to produce an estimate of the channel in a data subcarrier in the OFDM symbol. Therefore, when the channel is time-variant, the channel in a subcarrier can be estimated based on the channel in neighboring subcarriers, such as the channel in neighboring pilot subcarriers. For example, an estimate of the channel in any of the pilot subcarriers **402**, **404**, **405**, and **407** in the OFDM symbol in FIG. **4** can be used to produce an estimate of the channel in the data subcarrier **401**. Furthermore, in various embodiments, a channel in a subcarrier can be estimated based on both an estimated channel or channels in pilot subcarriers in the same subchannel as the subcarrier but in different OFDM symbol(s) and an estimated channel or channels in pilot subcarriers in the same OFDM symbol as the subcarrier.

In various embodiments, the channel in data subcarriers in shared subcarriers of an OFDM symbol **106** can be estimated using interpolation methods based on estimated channels in continuous **108** and scatter pilot subcarriers **104** in the same OFDM symbol. Linear interpolation can be used to estimate the channel in the data subcarriers in shared subchannels **106**. In an embodiment, Spline interpolation can be used to estimate the channel in such data subcarriers **106**. An interpolation function, such as Spline interpolation, can be implemented as a filter to estimate the channel.

FIG. **5** illustrates an example of an OFDM symbol with dedicated data subcarriers omitted for the sake of illustration. In the illustrated example, the black circles can represent pilot subcarriers in shared and/or continuous pilot subchannels **501**. The channel in the pilot subcarriers can be estimated based on expected values, for example by dividing the measure value of the subcarrier by the expected value of the subcarrier. In the illustrated example, the white circles can represent data subcarriers in shared subchannels **502**. The channel in the data signals **502** can be estimated using methods of interpolation based on the estimated channels in pilot signals **501**.

Interpolation can be implemented through a filter with a desired impulse response. In an embodiment, spline interpolation can be implemented through a filter. FIG. **6** illustrates a graphical example of the impulse response of a filter that can be implemented to perform interpolation. Such a filter can be implemented to estimate the channel in a data subcarrier **502** of an OFDM symbol such as illustrated in FIG. **5**. The channel in pilot subcarriers **501** can be estimated based on the expected and measured values, as described, and the channel can be transferred to an output without change in the filter.

Each peak in the graph can correspond to a data subcarrier in a shared subchannel **502**, such as the subcarriers illustrated in FIG. **5**. The height of each peak, measured on the Y-axis, can correspond to the weight that can be attributed to a corresponding subcarrier value by the filter, as will be illustrated further below.

FIG. **7** illustrates an example calculation of a channel in a subcarrier in a shared subchannel to the right of a pilot subcarrier by spline interpolation that can be implemented in a filter, in accordance with various embodiments. In the OFDM symbol of the illustrated figure, the pure data subcarriers were omitted, as was illustrated in FIG. **5**, for the sake of illustration. Hence, in the illustrated example, the black circles can represent pilot subcarriers in shared and/or continuous pilot subchannels **501** and the white circles can represent data subcarriers in shared subchannels **502**. As illustrated in the figure, the channel in a subcarrier **701** to the right of a pilot subcarrier **703** can be estimated based on the estimated channel in pilot subcarriers **700**, **702**, **703**, **704**, **705**, and **706** in the OFDM symbol. The channel in the pilot subcarriers can be estimated based on the expected pilot values and the measured pilot values. The estimated channel in each pilot subcarrier can be multiplied by a corresponding weight **709**, the products can then be added in an adder **707**, and the sum can be divided by a total weight **710**. The weights can be applied according to the impulse response as illustrated in FIG. **6**. Namely, the pilot subcarrier **703** to the left of the subcarrier **701** can be multiplied by the weight corresponding to the peak **601** to the left of the center peak **600** in the graph of FIG. **6**, or **905**. The pilot subcarrier three carriers to the right **704** of the subcarrier **701** can be multiplied by the weight corresponding to the peak **602** three peaks to the right of the center peak **600** in the graph of FIG. **6**, or **285**. The weights can be similarly assigned to the other pilot subcarriers **700**, **702**, **705**, and **706**.

The spline interpolation can be implemented for other data subcarriers in shared subchannels in an OFDM symbol by implementing the same methodology as illustrated in FIG. **7**.

FIG. **8** illustrates an example calculation of a channel in a subcarrier in a shared subchannel between two successive shared subchannels by spline interpolation that can be implemented in a filter, in accordance with various embodiments. In the example illustrated in the FIG. **8**, the methodology illustrated in FIG. **7** can be implemented to estimate the channel in a subcarrier **801** between two data subcarriers. The estimated channels in pilot subcarriers can be multiplied by corresponding weights assigned by the spline interpolation method, the products can be added, and the sum can be divided by a total weight as was illustrated in FIG. **7**. The weights can be chosen according to the distribution illustrated in FIG. **6**, according to the same methodology as was described in FIG. **7**.

FIG. **9** illustrates an example calculation of a channel in a subcarrier in a shared subchannel to the left of a pilot subcarrier by spline interpolation that can be implemented in a filter, in accordance with various embodiments.

If a pilot subcarrier that is supposed to be used in an estimate is missing, for example, when a channel in a subcarrier near the edge of an OFDM symbol is estimated, the weight of the missing pilot subcarrier can be applied to the closest existing pilot subcarrier. FIG. **10** illustrates an example calculation of the channel in a subcarrier when a pilot subcarrier is missing, in accordance with various embodiments. As illustrated in the example, because the subcarrier corresponding to the "33 weight" **1001** is missing, the estimated channel in the first pilot subcarrier **1002** can be used instead of the missing subcarrier. Hence, the estimated channel in the first pilot subcarrier **1002** can be used twice in the calculation of the channel in the subcarrier **1003**, once with the "33 weight" and once with the "−136 weight" **1004**.

Similarly, if two or more pilot subcarrier values are missing, then the weight of the missing pilot subcarriers can be applied to the closest existing pilot subcarrier. FIGS. **11** through **19** illustrate further examples of channel estimation with missing pilot subcarriers, in accordance with various embodiments.

The above examples illustrate channel estimation implementing spline interpolation with provided weights. It will be apparent to one of reasonable skill in the art that channel estimation can be performed using different methods of interpolation and/or different weights than the described examples without departing from the spirit of the invention. For example, a filter can be implemented to estimate a channel in a subcarrier through linear interpolation, through spline interpolation with different parameters than described above, through interpolation with weights that are selected manually, and through other methods.

FIG. **20**A illustrates an example estimation of a channel in a data subcarrier in a shared subchannel based on an estimate of the channel in a subcarrier in the subchannel of the previous OFDM symbol and an estimate of the channel in the subcarrier in the subchannel of the next OFDM symbol, in accordance with various embodiments. As illustrated in the example of the figure, the channel in a data subcarrier **2000** can be estimated based on the subcarrier **2001** in the subchannel of the previous OFDM symbol and the subcarrier **2002** in the subchannel of the next OFDM symbol. The channel in the data subcarrier **2000** can be estimated by averaging the estimated channels in the previous subcarrier **2001** and the next subcarrier **2002** by adding the estimated channels **2001**, **2002** in an adder **2003** and dividing the sum by 2 in a divider **2004**. In various embodiments, different methods can be used to estimate the subcarrier **2000** based on the estimated channels in the previous subcarrier **2001** and the next subcarrier **2002**. For example a linear combination of the estimated channels **2001**, **2002** can be used to estimate the channel **2000** with more weight being placed on one estimated channel than the other, for example a weight of 0.4 can be placed on the channel estimate in the previous subcarrier **2001** and a weight of 0.6 can be placed on the channel estimate in the next subcarrier **2002**. The estimate of the channel in subcarriers **2001** and **2002** can be performed based on pilot subcarriers. In various embodiments, the channel in the subcarriers **2001** and **2002** can be estimated according to methods described above, for example, through the spline interpolation method described above.

FIG. **20**B illustrates an example estimation of a channel in a data subcarrier in a shared subchannel based on an estimate of the channel in a subcarrier in the subchannel of the previous OFDM symbol and an estimate of channel in the subcarrier in the subchannel of the next OFDM symbol, when the subcarrier in the subchannel of the next OFDM symbol is a pilot subcarrier, in accordance with various embodiments. In such a case, an estimate of the channel **2005** can be performed as described above in FIG. **20**A. The channel in the pilot subcarrier **2006** can be estimated based on the expected value of the subcarrier **2006** and the measured value of the subcarrier **2006**, as described above.

FIG. **20**C illustrates an example estimation of a channel in a data subcarrier in a shared subchannel based on an estimate of a channel in a subcarrier in the subchannel of the previous OFDM symbol and an estimate of the channel in the subcarrier in the subchannel of the next OFDM symbol, when the subcarrier in the subchannel of the previous OFDM symbol is a pilot subcarrier, in accordance with various embodiments.

In such a case, an estimate of the channel **2007** can be performed as described above in FIG. **20**A. The channel in the pilot subcarrier **2008** can be estimated based on the expected value in the subcarrier **2008** and the measured value in the subcarrier **2008**, as described above.

FIGS. **20**A through **20**B illustrate using subcarriers in the same subchannel of the immediately previous OFDM symbol and the immediately succeeding OFDM symbol to estimate the channel in a subcarrier. In various other embodiments, subcarriers in the same subchannel of other preceding and/or succeeding OFDM symbols can be used instead of or in addition to the immediately previous and immediately next OFDM symbols to estimate the channel in a subcarrier.

In various embodiments, a channel in a data subcarrier can be estimated by combining two different estimates of the channel in the data subcarrier. For example, an estimate of the channel in the subcarrier obtained based on pilot signals in the OFDM symbol, for example as illustrated above in FIGS. **7** through **19**, can be combined with an estimate of the channel in the same subcarrier obtained based on an estimate of a subcarrier channel in the subchannel of the previous OFDM symbol and an estimate of the subcarrier channel in the subchannel of the next OFDM symbol, as illustrated in FIGS. **20**A through **20**C. In an embodiment, the two estimates can be combined in a linear combination with a coefficient of 112. For example, the first estimate can be multiplied by 112 and the second estimate can be multiplied by 112 and the two products can be added. In other embodiments, the multiples can be different to give more weight to one estimate that the other.

Thus, in an embodiment, a channel in a subcarrier can be first estimated based on pilot subcarriers in the OFDM symbol using spline interpolation, for example as illustrated above in FIGS. **7** through **19**. The channel in the same subcarrier can be estimated a second time by combining an estimate of the subcarrier in the same subchannel of the previous OFDM symbol and an estimate of the subcarrier in the same subchannel of the next OFDM symbol, for example as illustrated in FIGS. **20**A through **20**C. The estimate of the subcarrier in the subchannel of the previous OFDM symbol and the estimate of the subcarrier in the subchannel of the next OFDM symbol can be obtained by spline interpolation based on pilot subcarriers in the OFDM symbol or, if the subcarrier is a pilot subcarrier, based on the expected pilot value. A third estimate of the subchannel can then be produced by combining the first and the second estimates of the channel in the subcarrier, for example in a linear combination with a coefficient of V2.

In various embodiments, the channel in each of the data subcarriers **107** in dedicated data subchannels **102** as illustrate in FIG. **1**, which were omitted in the illustration of FIG. **5**, can be estimated based on the estimated channel in the two nearest subcarriers. FIG. **21**A illustrates an example of channel estimation in a data subcarrier in a dedicated data subchannel through the weighted sum of the channel in two nearest estimated subcarriers. In the example illustrated, the gray circle is a data subcarrier in a shared subchannel **2101**; the black circle is a pilot subcarrier in a shared or a continuous subchannel **2104**; the white circles are data subcarriers in dedicated data subchannels **2102**, **2103**. To estimate the channel in the data subcarrier **2103**, the estimated channel in the data subcarrier **2101** can be multiplied by 5 in a multiplier **2105** and the estimated channel in the pilot subcarrier **2104** can be multiplied by 11 in a multiplier **2106**. The products can be added in an adder **2107** and divided by 16 in a divider **2108** to estimate the channel in the data subcarrier **2103**. The channel in the subcarrier **2102** can be similarly estimated by producing a weighted sum with a weight of 11 being applied to the data subcarrier **2101** and a weight of 5 being applied to the pilot subcarrier **2104**. The channel in the data subcarrier **2101** and the pilot subcarrier **2104** can be estimated based on the methods described above in the specification.

FIG. **21**B illustrates an example of channel estimation in a data subcarrier in a dedicated data subchannel through the weighted sum of the channel in two nearest estimated pilot subcarriers, in accordance with various embodiments.

FIG. **21**C illustrates an example of channel estimation in a data subcarrier in a dedicated data subchannel through the weighted sum of the channel in two nearest estimated data subcarriers, in accordance with various embodiments.

FIG. **21**D illustrates an example of channel estimation in a data subcarrier in a dedicated data subchannel through the weighted sum of the channel in a nearest estimated data subcarrier and a nearest estimated pilot subcarrier, in accordance with various embodiments.

In various embodiments, the channel in each of the data subcarriers **107** in dedicated data subchannels **102**, as illustrated in FIG. **1**, can be estimated in a linear combination of the estimated channels in the two nearest subcarriers as illustrated in the examples in FIGS. **21**B through **21**C. In various embodiments, the linear combination, as illustrated in the examples in FIGS. **21**B through **21**C, can be performed using different weights in the linear combination than illustrated. In various embodiments, different methods, such as non-linear combination, can be used to estimate the channel in each of the data subcarriers **107** in dedicated data subchannels **102** based on the estimated channels in the two nearest subcarriers.

Embodiments of the system and method described herein facilitate estimating the channel in OFDM transmission. Although the components and modules illustrated herein are shown and described in a particular arrangement, the arrangement of components and modules may be altered to perform the described functions and processes in a different manner. In other embodiments, one or more additional components or modules may be added to the described systems, and one or more components or modules may be removed from the described systems. Alternate embodiments may combine two or more of the described components or modules into a single component or module.

While certain exemplary embodiments have been described and shown in the accompanying drawings, it is to be understood that such embodiments are merely illustrative of and not restrictive on the broad invention, and that this invention is not limited to the specific constructions and arrangements shown and described, since various other modifications may occur to those ordinarily skilled in the art. Accordingly, the specification and drawings are to be regarded in an illustrative rather than a restrictive sense.

Reference in the specification to "an embodiment," "one embodiment," "some embodiments," "various embodiments" or "other embodiments" means that a particular feature, structure, or characteristic described in connection with the embodiments is included in at least some embodiments, but not necessarily all embodiments. References to "an embodiment," "one embodiment," or "some embodiments" are not necessarily all referring to the same embodiments. If the specification states a component, feature, structure, or characteristic "may," "can," "might," or "could" be included, that particular component, feature, structure, or characteristic is not required to be included. If the specification or Claims refer to "a" or "an" element, that does not mean there is only one of the element. If the specification or Claims refer to an "additional" element, that does not preclude there being more than one of the additional element.

What is claimed is:

1. A receiver, comprising:

an antenna configured to receive a signal;

a channel estimator component configured to interpolate the signal to produce a first estimate of a channel in a first estimated data subcarrier in a shared subchannel in an Orthogonal Frequency-Division Multiplexing (OFDM) symbol of the signal, wherein interpolating the signal is based at least in part on estimated channels in at least one pilot subcarrier in a same subchannel as the first estimated data subcarrier but a different OFDM symbol than the first estimated data subcarrier, wherein the estimated channels in the at least two pilot subcarriers in the same OFDM symbol are determined by:

assigning a corresponding weight to each of the at least two pilot subcarriers, wherein the corresponding weight is based at least in part on impulse response of a filter;

multiplying each of the at least two pilot subcarriers by the corresponding weight to compute two or more products;

adding the two or more products in an adder to compute a sum; and

dividing the sum by a total weight assigned to each of the at least two pilot subcarriers.

2. The receiver of claim **1**, wherein interpolation is further based at least in part on at least two pilot subcarriers in the same OFDM symbol as the data subcarrier but a different subchannel than the data subcarrier.

3. The receiver of claim **1**, wherein the corresponding weight is based on a peak in the impulse response of the filter corresponding one of the at least two pilot subcarriers received by the filter.

4. The receiver of claim **1**, further comprising:

a tuner configured to perform at least one of: amplify, filter or down-convert the signal;

an analog-to-digital converter (ADC) configured to convert the signal to digital form;

a filtering and synchronization module configured to filter and synchronize the signal; and

a Fast Fourier Transform (FFT) module configured to output at least one OFDM symbol.

5. The receiver of claim **1**, wherein the channel estimator component is further configured to produce the first estimate of the channel in the first estimated data subcarrier in the shared subchannel through Spline interpolation.

6. The receiver of claim **5**, wherein the channel estimator component is further configured to:

produce a second estimate of the channel in the first estimated data subcarrier in the shared subchannel based on an estimate of a channel in a subcarrier in a previous OFDM symbol in the same subchannel and an estimate of a channel in a subcarrier in a succeeding OFDM symbol in the same subchannel.

7. The receiver of claim **6**, wherein the second estimate of the channel in the first estimated data subcarrier in the shared subchannel is produced by taking an average of the estimate of the channel in the subcarrier in the previous OFDM symbol in the same subchannel and the estimate of the channel in the subcarrier in the succeeding OFDM symbol in the same subchannel.

8. The receiver of claim **7**, wherein the channel estimator component is further configured to:

produce a third estimate of the channel in the first estimated data subcarrier in the shared subchannel based on the first estimate of the first estimated data subcarrier in the shared subchannel and the second estimate of the first estimated data subcarrier in the shared subchannel.

9. The receiver of claim **8**, wherein the third estimate of the channel in the first estimated data subcarrier in the shared subchannel is produced through a linear combination of the first estimate of the channel in the first estimated data subcarrier in the shared subchannel and the second estimate of the channel in the first estimated data subcarrier in the shared subchannel.

10. The receiver of claim **8**, wherein the channel estimator component is further configured to estimate a channel in a data subcarrier in a designated data subchannel based on an estimated channel of two nearest subcarriers in shared subchannels in a same OFDM symbol.

11. The receiver of claim **1**, wherein the channel estimator component is further configured to estimate a channel in a data subcarrier in a designated data subchannel through a weighted sum of the channels in two nearest subcarriers in shared subchannels in the same OFDM symbol.

12. The receiver of claim **1**, wherein the signal is an OFDM signal with one or more scattered pilots.

13. A method, comprising:

receiving a signal; and

producing a first estimate of a channel in a first estimated data subcarrier in a subchannel in an OFDM symbol of the signal through interpolation, the interpolation being based on at least one pilot subcarrier that is in a same subchannel as the data subcarrier but in a different OFDM symbol than the data subcarrier, wherein the estimated channels in the at least two pilot subcarriers in the same OFDM symbol are determined by:

assigning a corresponding weight to each of the at least two pilot subcarriers based on impulse response of a filter;

multiplying each of the at least two pilot subcarriers by the corresponding weight to compute two or more products;

adding the two or more products in an adder to compute a sum; and

dividing the sum by a total weight assigned to all of the at least two pilot sub carriers.

14. The method of claim **13**, wherein interpolation is further based at least in part on at least two pilot subcarriers that are in the same OFDM symbol as the data subcarrier but a different subchannel than the data subcarrier.

15. The method of claim **13**, further comprising:

producing a second estimate of the channel in the first estimated data subcarrier based on an estimate of the channel in a subcarrier in the same subchannel in a previous OFDM symbol and an estimate of the channel in a subcarrier in the same subchannel in a succeeding OFDM symbol.

16. The method of claim **15**, wherein the second estimate of the channel in the first estimated data subcarrier is produced by taking an average of an estimated channel in a subcarrier in the same subchannel in a previous OFDM symbol and an estimate of a channel in a subcarrier in the same subchannel in a succeeding OFDM symbol.

17. The method of claim **15**, further comprising:

producing a third estimate of the channel in the first estimated data subcarrier in the shared subchannel based on the first estimate of the first estimated data subcarrier in the shared subchannel and the second estimate of the first estimated data subcarrier in the shared subchannel,

wherein the third estimate of the channel in the first estimated data subcarrier in the shared subchannel is produced through a linear combination of the first estimate of the channel in the first estimated data subcarrier in the shared subchannel and the second estimate of the channel in the first estimated data subcarrier in the shared subchannel.

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